DEVELOPMENT OF A CFD CODE FOR ANALYSIS OF FLUID DYNAMIC FORCES IN SEALS

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This presentation is a status report for Task I of the Seals Flow Code project. The aim of this task is to develop a 3D CFD code for the analysis of fluid flow in cylindrical seals and evaluation of the dynamic forces on the seals. This code is expected to serve as a scientific tool for detailed flow analysis as well as a check for the accuracy of the 2D industrial codes

The features necessary in the CFD code are outlined. These include general considerations such as code accuracy, efficiency, and robustness and other specific features such as rotating coordinate frames, steady and time-accurate solutions, inclusion of non-isotropic wall roughness, effects of phase-change and cavitation, and integration with KBS.

The approach and initial focus of the task is discussed next. The initial focus of the task was to develop or modify and implement new techniques and physical models. These include collocated grid formulation, rotating coordinate frames and moving grid formulation. Other advanced numerical techniques include higher-order spatial and temporal differencing and efficient linear equation solver.

These techniques were implemented in a 2D flow solver for initial testing. Several benchmark test cases were computed using the 2D code and the results of these are compared with analytical solutions or experimental data to check the accuracy. Tests presented here include planar wedge flow, flow due to an enclosed rotor and flow in a 2D seal with a whirling rotor. Comparisons between numerical and experimental results for an annular seal and a 7 cavity labyrinth seal are also included.

The presentation is closed with plans for the second and final year of Task I. This involves completion of modifications in the 3D base code, and incorporation in the 3D code of the physical models to treat turbulence, non-isotropic wall roughness, phase-change and cavitation, brush-seal model, and calculation of dynamic coefficients.

OBJECTIVES

- **Develop Verified CFD Code for Analyzing Seals**

- **Required Features Include:**
  - **Applicability to a Wide Variety of Seal Configurations, such as: Cylindrical, Labyrinth, Face, Tip and Brush Seals**

  - **Accuracy of Predicted Flow Fields and Dynamic Forces**

  - **Efficiency (Economy) of Numerical Solutions**

  - **Reliability (Verification) of Solutions**

  - **Ease-of-Use of the Code (Documentation, Training)**

  - **Integration with KBS**

CFD CODE REQUIRED CAPABILITIES

- **Solve 2-D and 3-D Navier-Stokes Equations with Provisions for:**
  - **Complex Geometries (Body Fitted Coordinates, High Aspect Ratio Cells, Skewed Grids, *etc.*)**

  - **Stationary and Rotating Coordinates**

  - **Steady-State and Transient Analysis**

  - **Turbulence, Surface Roughness**

  - **Compressibility, Viscous Dissipation**

  - **Heat Transfer, Phase Change, Cavitation**

  - **Electromagnetic Effects, *etc.***

CFD SEALS CODE DEVELOP. - APPROACH

- Use state-of-the art techniques and latest relevant physical models

- Starting Point: REFLEQS-2D and 3D codes

- 2D code used as a base for efficient evaluation of latest numerical techniques

- Optimum procedure and programming practice tested in 2D code (computer memory vs. computational speed dilemma)

- Fast turnaround time

- Several benchmark-quality validation experiments available for 2D and only few for 3D

- Verified 2D code used as a checkout test bed for 3D code

INITIAL FOCUS OF TASK 1

- Study, Implement and Test:
  - a) Non-Staggered Grid Formulation
  - b) Rotating Coordinates
  - c) Transient Solution Algorithm

- Physical Model Modifications for:
  - a) Turbulence in Rotating Flows
  - b) Non-Isotropic Wall Roughness
  - c) Compressibility and Viscous Dissipation
  - d) Two-Phase Flows (Phase Cavitation, *etc.*)

- Calculation of Dynamic Forces and Coefficients

ADVANCED NUMERICAL TECHNIQUES - STATUS

- Colocated Grid Formulation for BFC Grids

- Strong Conservative Formulation of Momentum Equations with Cartesian Components

- Choice of SIMPLE, Modified SIMPLEC and Noniterative PISO

- Higher Order Accurate Temporal Differencing

- Higher Order (2nd, 3rd) Spatial Discretizations Available

- Rotating Grid System for Stator-Rotor Configurations

- Moving Grid option for Arbitrary Rotor Whirling Analysis

- Efficient Multigrid Solver

PLANAR WEDGE FLOW

Length = 0.1,   Heights: Minimum = 3×10^{5} m,
Maximum = 3×10^{-4} m, y scale enlarged 200 times
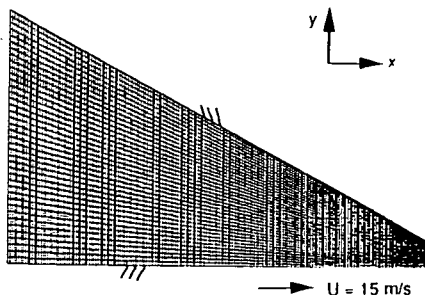
192 x 40 Grid   Streamlines
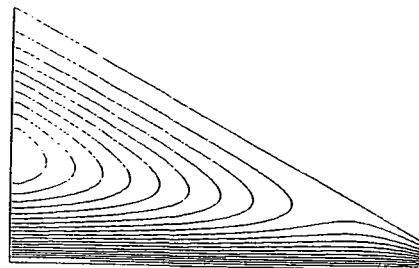

```
STR1  CONTOURS
FMIN  5 851E-03
FMAX  7 827E-01
CONTOUR LEVELS
 I    5 852E-03
 2    4 459E-02
 3    8 353E-02
 4    1 224E-01
 5    1 612E-01
 6    2 001E-01
 7    2 399E-01
 8    2 777E-01
 9    3 166E-01
10    3 554E-01
11    3 943E-01
12    4 331E-01
13    4 719E-01
14    5 108E-01
15    5 495E-01
21    7 825E-01
```

PLANAR WEDGE FLOW

u Velocity
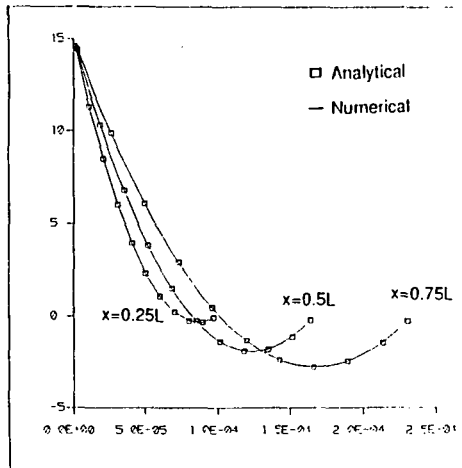
Pressure
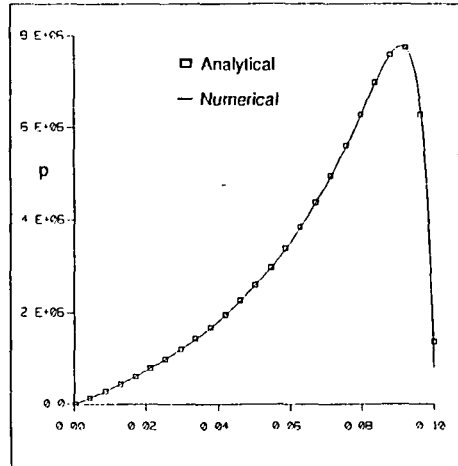
ENCLOSED ROTOR

Daily & Nece (1960)
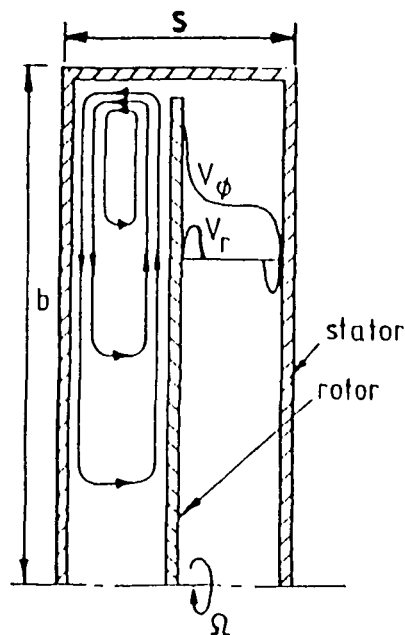
ENCLOSED ROTOR
Daily and Nece

Tangential Velocity

r/b = 0.765

□ Data of Daily & Nece
— Colocated Grid

Radial Velocity

r/b = 0.765

□ Data of Daily & Nece
— Colocated Grid
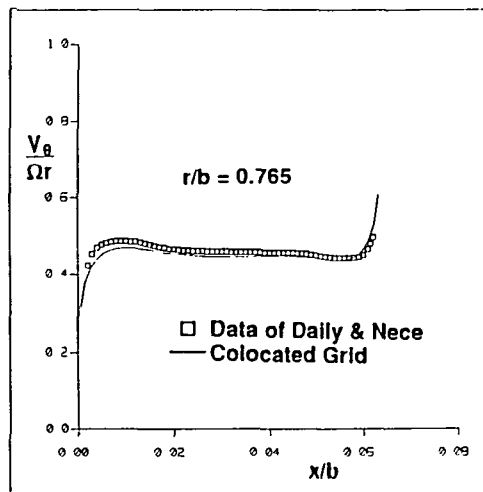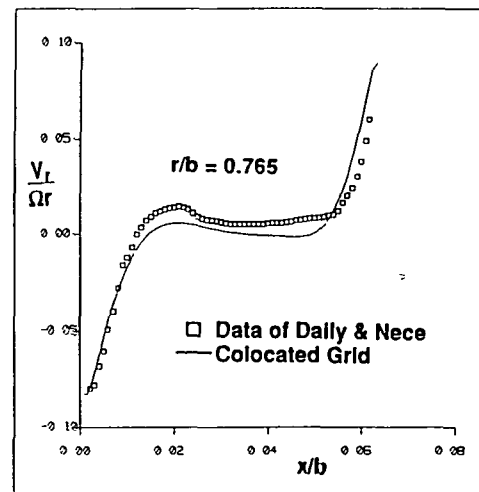
WHIRLING ROTOR IN AN ANNULAR SEAL

Stator radius = 50.1478 x 10^{-3}m,
Clearance = 495 μm, ε = 0.8 x clearance,
Shaft Speed ω = 5085 rpm
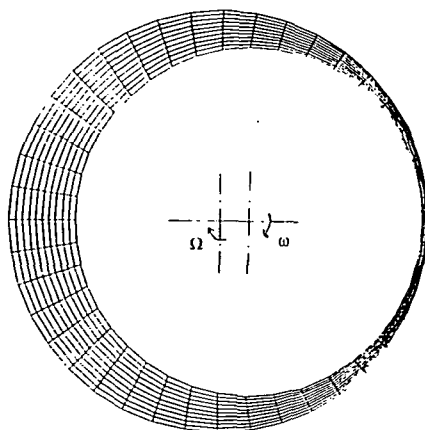
40 x 10 Computational Grid
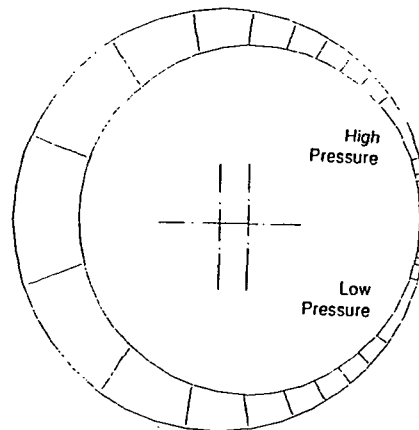
Pressure Contours
Synchronous Whirl, Ω = ω

WHIRLING ROTOR IN AN ANNULAR SEAL

Pressure Contours
Subsynchronous Whirl, $\Omega = 0.5\omega$

Pressure Contours
Subsynchronous Whirl, $\Omega = 0.01\omega$

ANNULAR SEAL

Morrison, *et. al*
Re = 27000, T_a = 6600, L/C = 29.4

Annular Rotor
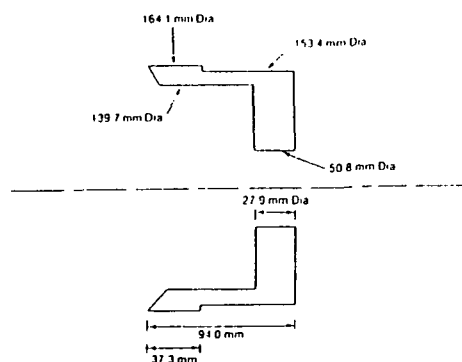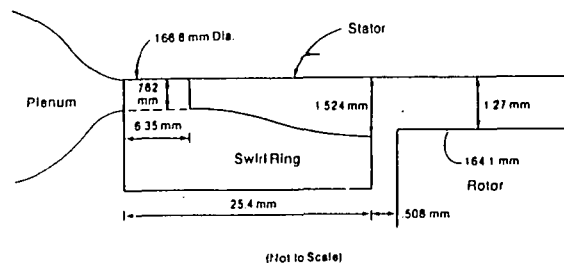
Seal Geometry

ANNULAR SEAL

$u_x/\bar{U}$ contours

Experimental	Numerical

Inlet
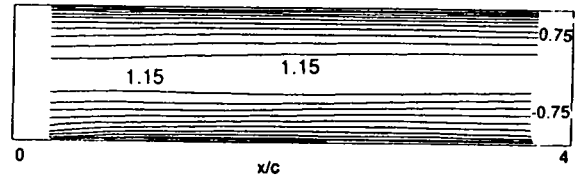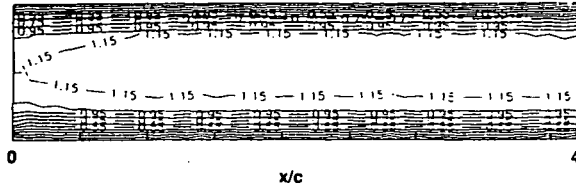
Outlet
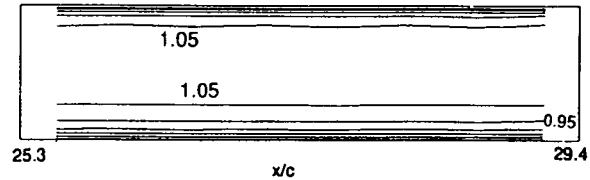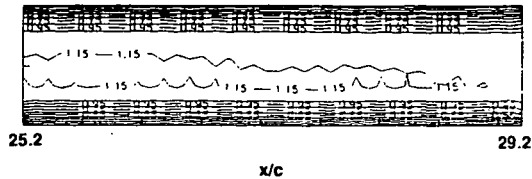
SEVEN CAVITY LABYRINTH SEAL

Morrison, *et. al.*
Re = 28000   Ta = 7000

Labyrinth Rotor	Inlet Geometry
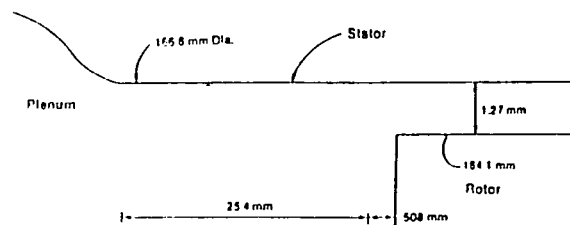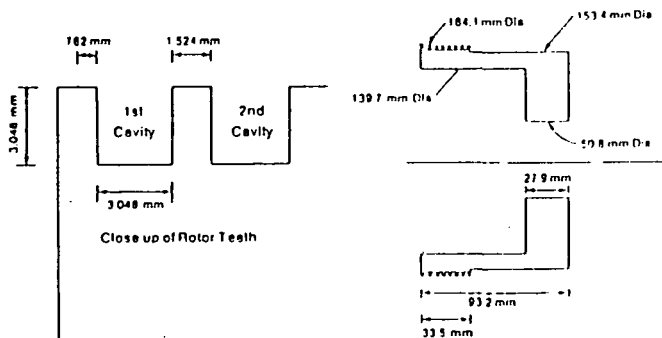
SEVEN CAVITY LABYRINTH SEAL
Velocity Vector Plot

Experimental   **Numerical**
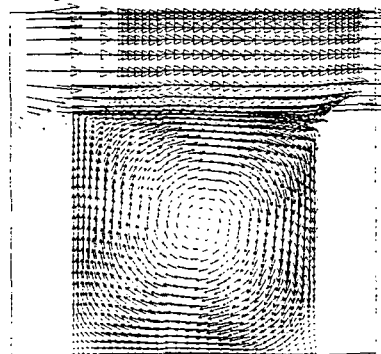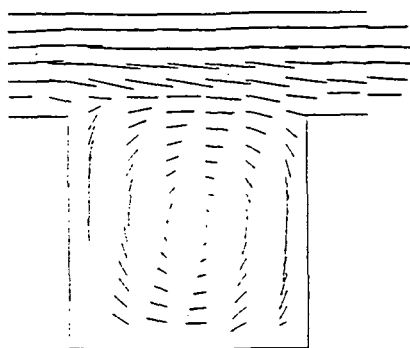
First Cavity
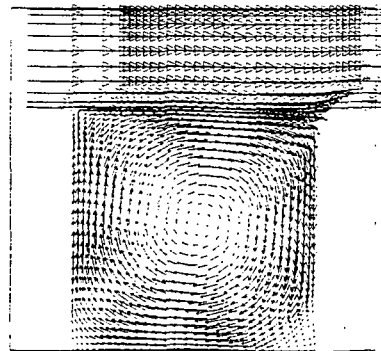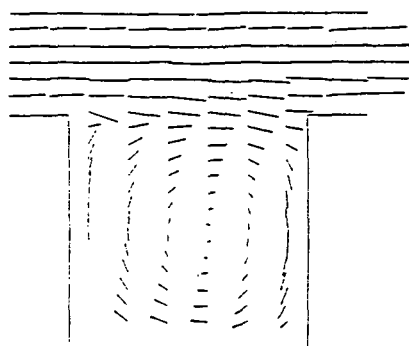
Third Cavity

SEVEN CAVITY LABYRINTH SEAL
$u_x/\overline{U}$ contours

Experimental   **Numerical**
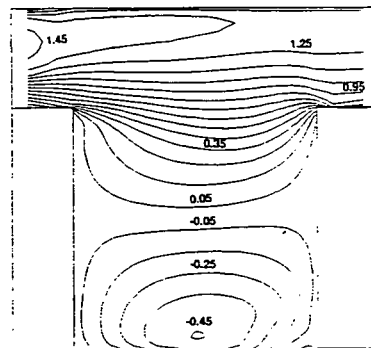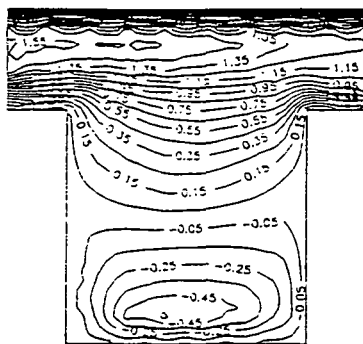
First Cavity
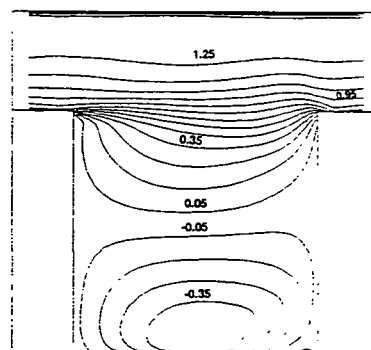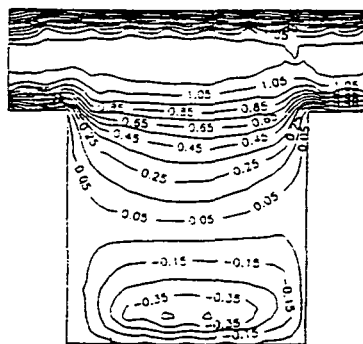
Third Cavity
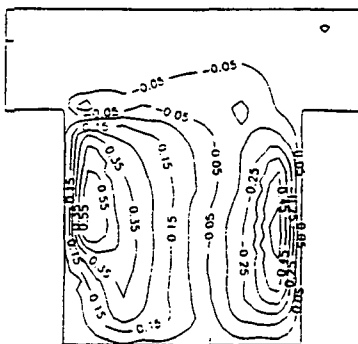
SEVEN CAVITY LABYRINTH SEAL
$u_r/\bar{U}$ contours
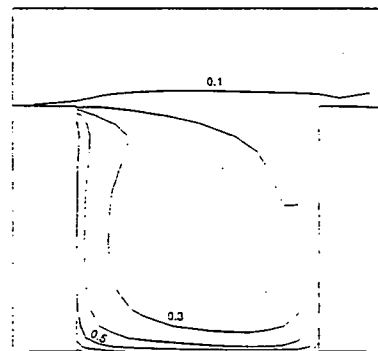
First Cavity
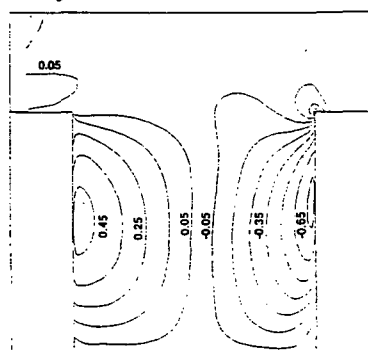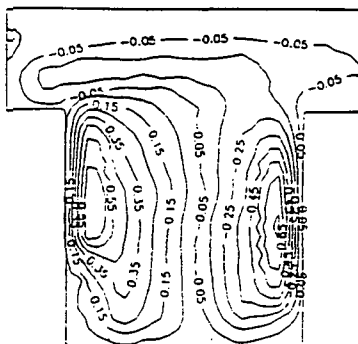
Third Cavity
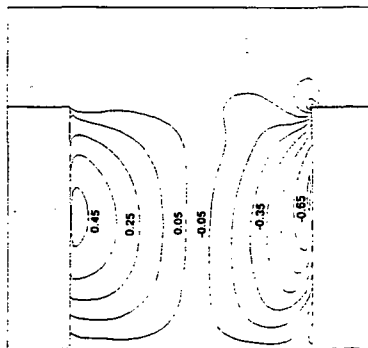
SEVEN CAVITY LABYRINTH SEAL
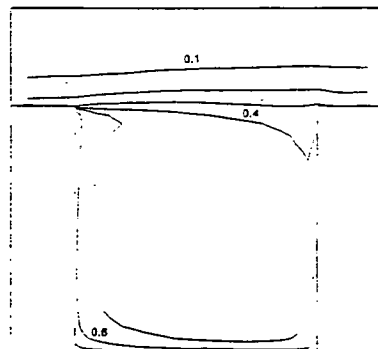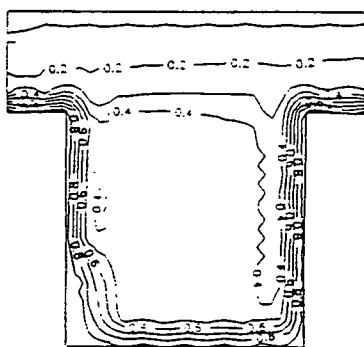
u_θ / w_{shaft} contours

Experimental   **Numerical**

First Cavity
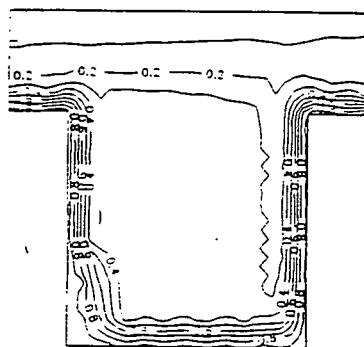
Third Cavity

TASK 1 COMPLETION PLAN (DEC 91)

- Complete Advanced Numerical Techniques Implementation

- 3D Code Modifications

- Incorporation of Advanced Physical Models
    - •• Turbulence Models

    - •• Non-Isotropic Wall Roughness

    - •• Compressibility and Viscous Dissipation

    - •• Two-Phase (Phase Change)

    - •• Cavitation

    - •• Brush Seal Model
- Incorporation of Dynamic Forces and Coefficients